The bird beak configuration has no adverse effect in a magnetic resonance functional analysis of thoracic stent grafts after traumatic aortic transection

Alexander Oberhuber, MD,[a] **David Schabhasian, MD,**[b] **Robert Kohlschmitt, MD,**[b] **Wolfgang Rottbauer, MD,**[c] **Karl-Heinz Orend, MD,**[b] and **Volker Rasche, PhD,**[c] *Düsseldorf and Ulm, Germany*

Background: **This study used magnetic resonance imaging (MRI) to analyze functional long-term outcome after endovascular repair of blunt aortic injury.**
Methods: **This prospective study enrolled 27 of 53 patients who were treated between 1999 and 2008. Patients underwent functional multidimensional contrast-enhanced MRI with flow analysis or compliance measurements of the aorta, or both. Ten patients were treated with the Medtronic Valiant (Medtronic World Medical, Sunrise, Fla), 14 patients received a Gore TAG (W. L. Gore & Associates, Flagstaff, Ariz), and two received a C (conformable)-TAG (W. L. Gore & Associates) stent graft. For several patients, repetitive measurements over time could be done. Median follow-up was 3.92 ± 2.7 years. The MRI parameters were: three-dimensional flow: echo time/repetition time = 3.1/5.3 ms, Δx(pixel density) = 2.5 × 2.5 × 3 mm^3; respiratory navigator, $\alpha = 15°$, v_{enc}(encoding velocity) = 200 cm/s along anterior-posterior, right-left, and foot-head direction, 40 cardiac phases. Cine: echo time/repetition time = 1.7/3.4 ms, Δx(pixel density) = 1.2 × 1.2 × 6 mm^3, breathhold, $\alpha = 60°$, 40 cardiac phases.**
Results: **The flow analysis showed flow acceleration at the proximal end of the stent graft, with higher values in patients with a nonoptimal alignment of the stent graft. No differences were found between different devices (median acceleration was 75.99 ± 37.98 cm/s for Gore and 71.59 ± 17.22 cm/s for Medtronic). The values were stable during follow-up. In the compliance analysis, the part of the aorta covered with the stent graft showed nearly no expansion, whereas the ascending and descending aorta showed normal expansion. This behavior did not change over the time. At the proximal end of the stent graft, a slight compression could be noted (−0.5 ± 0.14 mm), except in those patients with a C-TAG device from Gore.**
Conclusions: **Functional analysis showed no adverse long-term outcome of the bird beak configuration of stent grafts in the aortic arch after endovascular repair after blunt aortic injury. (J Vasc Surg 2015;61:365-73.)**

In recent years, thoracic endovascular aortic repair (TEVAR) of acute traumatic aortic ruptures has become an attractive alternative to open chest surgical approaches. With the reported excellent clinical outcome[1] and especially the related reduced mortality and morbidity of this innovative method, TEVAR is currently emerging as the new gold standard.[2-4] Although stent grafts placed in the straight-shaped descending aorta show good alignment with the vessel wall, the physiologic angle of the thoracic aorta often causes these stent grafts to form a so-called bird beak in the aortic arch.[5]

From the Department of Vascular and Endovascular Surgery, University of Düsseldorf, Düsseldorf[a]; and the Departments of Cardiothoracic and Vascular Surgery[b] and Internal Medicine II,[c] University of Ulm, Ulm.
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Reprint requests: Alexander Oberhuber, MD, Department of Vascular and Endovascular Surgery, University of Düsseldorf, Moorenstrasse 5, 40225 Düsseldorf, Germany (e-mail: alexander.oberhuber@corones.it).
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The angle between the inner curvature of the aortic arch and the stent graft depends on the stent graft, the patient's age, and the cardiac phase.[6,7] Younger people often present with a tighter so-called gothic arch in contrast to the wider aortic arch to normally found in older people. Variation of the angle over the cardiac cycle has been reported as high as 20° (minimum in the diastole and maximum in the systole),[8] likely causing the risk of a stent graft compression syndrome with subsequent high aortic occlusion. Stent graft compression syndrome was reported up to 3 months of the early postoperative phase.[1,9] The functional effect of the bird beak after traumatic aortic transections on adverse long-term effects is still unknown.

A former study showed the applicability of magnetic resonance imaging (MRI) for the assessment of stent graft deployment.[7] The aim of this study was to evaluate the flow pattern in thoracic stent grafts and the movements (compression/expansion) of the aorta and the stent graft during the cardiac cycle after traumatic rupture of the aorta by functional and flow-encoded MRI and to draw conclusions for the daily routine.

METHODS

The local Ethic Committee approved this study. Written informed consent was obtained from all patients before enrollment.

Patients. The study enrolled 27 of 53 patients who received an endovascular treatment between 1999 and 2008. The study was started including all patients retrospectively, and from 2008, all new patients were enrolled prospectively.

Six patients died due to the polytrauma, six patients received Cook stent grafts (Cook Medical, Bloomington, Ind), which are not eligible for MRI flow analysis due to stainless steel-induced artefacts, and 14 patients refused MRI at the University Hospital of Ulm and received instead a computed tomography (CT) scan at other institutions. Clinical data were published elsewhere.[1]

Median age was 37.11 years (range, 12-79 years). Median follow-up was 3.92 ± 2.7 years. The first imaging was conducted during the hospital stay, then after 3, 6, and 12 months, and then annually. All patients showed a bird beak configuration after implantation. Ten patients were treated with Medtronic Valiant (Medtronic World Medical, Sunrise, Fla), 14 patients received Gore TAG (W. L. Gore & Associates, Flagstaff, Ariz), and three patients received C (conformable)-TAG (W. L. Gore & Associates) stent grafts.

Thirteen patients were investigated repetitively from 2008 to 2011 by MRI. One patient had four MRI follow-up assessments, four and five patients had three assessments, and seven patients had two MRI assessments. The remaining 14 patients were analyzed once.

Healthy men aged 30 to 35 years were analyzed for comparison and to assess flow patterns in nontreated patients.

MRI protocol. All patients underwent an investigational MRI protocol, comprising a three-dimensional (3D) angiogram of the aorta, a cardiac phase resolved quantitative 3D flow measurement, and a cine acquisition proximal and distal to the stent and at its proximal, central and distal location. All data were acquired on a 1.5T clinical 1.5 Intera MRI system (Philips Healthcare, Best, The Netherlands) equipped with a Power Trak 6000 gradient system (23 mT/m; 219 ms rise time) using dedicated 5- and 32-element cardiac phased-array receive coils. A vector electrocardiogram was applied for cardiac synchronization.

MRI parameters were 3D flow: echo time/repetition time = 3.1/5.3 ms, Δx(pixel density) = $2.5 \times 2.5 \times 3$ mm^3, respiratory navigator, $\alpha = 15°$, v_{enc}(encoding velocity) = 200 cm/s along anteroposterior, right-left, and foot-head direction, and 40 cardiac phases. Cine: echo time/repetition time = 1.7/3.4 ms, Δx(pixel density) = $1.2 \times 1.2 \times 6$ mm^3, breathhold, $\alpha = 60°$, and 40 cardiac phases.

Data analysis. Flow velocities and vessel diameters were quantified on parasagittal and transversal slices at five locations, as indicated in Fig 1. Area measurements were performed at the location of the proximal and distal stent and at the descending aorta distal to the stent.

Flow was measured in different semicircles of the aortic cross sections. Owing to the curvature of the aortic arch, flow acceleration was greater in the outer semicircle.

Flow quantification was done with GTFlow software (Gyrotools LLC, Winterthur, Switzerland). Flow analysis was restricted to the through-plane velocity.

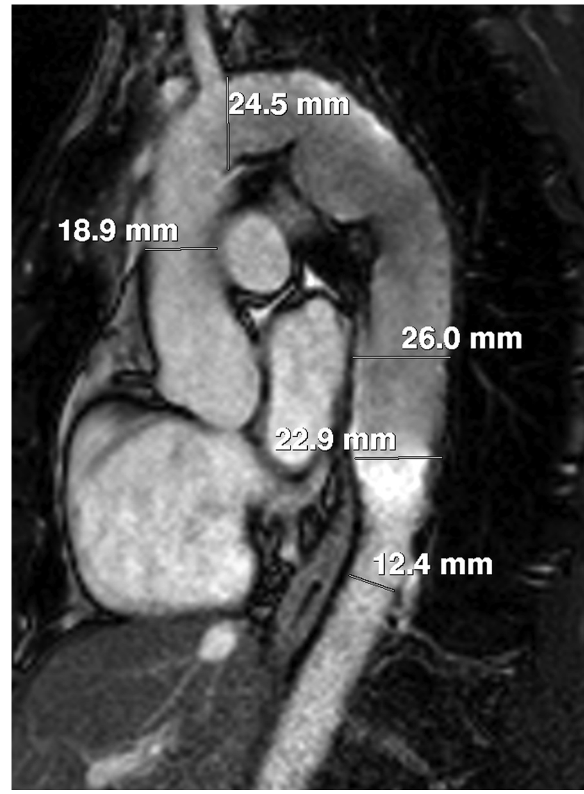

Fig 1. Five measurement points: ascending aorta, proximal end of the stent graft, middle of the stent graft, distal end of the stent graft, and descending aorta.

Compliance analysis was performed using Extended Workspace 2.6.3.2 software (Philips Healthcare). For the diameter quantification, the central slice in the parasagittal stack was identified manually for each of the five locations, and diameter measurements were performed for each cardiac phase by manual identification of the vessel borders. Area measurements were done semiautomatically by manual contouring the vessel border in end diastole with automatic tracking of the borders over the entire cardiac cycle using the "Cardiac Analysis" function of the analysis tool. Each resulting segmentation was checked for accuracy and manually corrected if required before final calculation of the functional information.

Alignment of the stent grafts. The bird beak configuration was defined as a misalignment of the stent graft at the inner curve of the aortic arch building a gap between the stent graft material and the aortic wall. Depending on the anatomy of the aortic arch and the stiffness of the stent grafts, the bird beak configurations varied in degree and were at different risk for type Ia endoleak. All patients showed a bird beak configuration. All stent grafts with loss of contact of more than the bare springs and protrusion in the arch were defined as "nonoptimal alignment" and at risk for stent graft collapse. Two of 27 stent grafts in this series were defined as having nonoptimal alignment.

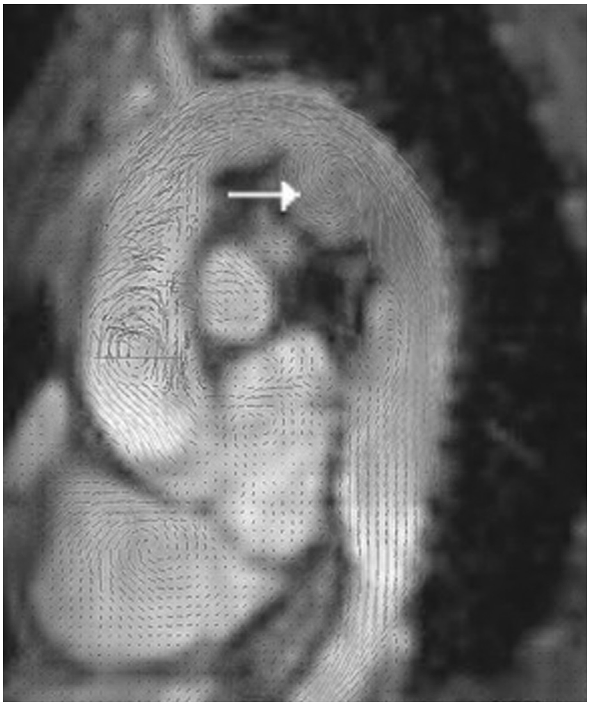

Fig 2. Flow analysis of a patient with stent graft after aortic transection. The stent graft is bulged (*white arrow*) into the transection zone and here the flow is retrograde.

RESULTS

Flow analysis. Flow in the aorta in healthy volunteers is quite homogeneous, except for a mild acceleration in the transition of the aortic arch and the descending aorta. In contrast, the flow rate is not homogeneous in patients with a stent graft at these positions and is clearly accelerated in the area of the outer curvature. The velocity deterioration depends on the bird beak and the slope of the aortic arch. In cross-sections of the aorta, an asymmetric distribution was found especially in the transition zone from the aortic arch to the descending aorta. Higher velocities were analyzed on the outer curvature rather than on the inner curvature. Retrograde flow can be seen in cases where the stent grafts bulges into the rupture zone (Fig 2).

In patients with a nonoptimal alignment, flow acceleration could be found only in the outer semicircle. The median change in all patients was about 30 cm/s (Fig 3), with increasing values of up to 130 cm/s in patients showing increasingly severe misalignment of the stent graft (Fig 4). The blood flow was very stable in patients with a good alignment of the stent graft during the cardiac cycle, whereas in a situation with nonoptimal alignment, the maximum acceleration was found at the end of the systole (Fig 5).

No significant differences could be found regarding the different stent grafts that were used. The maximum flow acceleration was from proximal to the middle of the stent graft. The median acceleration was 75.99 ± 37.98 cm/s in the Gore group and 71.59 ± 17.22 cm/s in the Medtronic group.

No significant changes over time were observed in patients with repetitive measurements over time.

Compliance. Median changes of the diameters in the parasagittal slices during the cardiac cycle are depicted in Fig 6. The portions of the aorta that were not covered by the stent graft, ascending as well as the descending aorta, showed physiologic compliance patterns. They showed a first expansion during systole and a smaller second expansion during diastole. The part of the aorta that was covered by a stent graft showed no enlargement. In patients with nonoptimal alignment, there was a persistent significant negative change (compression) of the stent graft at the proximal end of -0.5 ± 0.14 mm in the beginning of the systole. The middle and the distal end of the stent graft showed stable diameters. This behavior did not change over the time in repetitive measurements.

The orthogonal measurements of areas confirmed the findings of the diameter measurements (Fig 7). Nearly no changes were found in those parts of the aorta that were covered with the stent graft (2%-3%), but physiologic changes could be seen in the descending aorta (up to 15%), which was free of the stent graft.

The compression was greater in patients with a nonoptimal alignment than in patients with an optimal alignment of the stent graft (Fig 8). Only two patients showed a nonoptimal alignment, so no correlation analysis could be done.

No significant differences were found between the Medtronic and the Gore TAG device. A difference was only seen when the C-TAG was compared with the other devices in the sagittal measurements at the proximal end of the stent graft (Fig 9). Whereas the Medtronic and the Gore TAG grafts showed a mild compression, the C-TAG device was quite stable in this position and nearly not deformed. A statistical analysis was not performed due to the small number of analyzed C-TAG devices. In repetitive measurements over time, no significant changes could be found, with differences up to 0.5 mm.

DISCUSSION

The minimally invasive treatment of acute aortic transections by stent grafts shows significantly lower morbidity and mortality rates.[10] Major concerns exist about the long-term durability of the stent grafts, especially when used in young people combined with low compliance of those patients for follow-up visits.[11]

We showed in a preliminary study[7] that measurements of diameters in MRI and CT are comparable and that geometry and motion over the cardiac cycle are assessable by MRI.

To the best of our knowledge, MRI-based flow analyzes of stent grafts in the aortic arch have not been published yet. A similar method has been used to analyze the flow pattern in the ascending aorta and in patients with pathologies of the ascending and of the thoracic aorta, but not in patients with stent grafts.[12] The advantage of this method is a direct, noninvasive, radiation-free functional

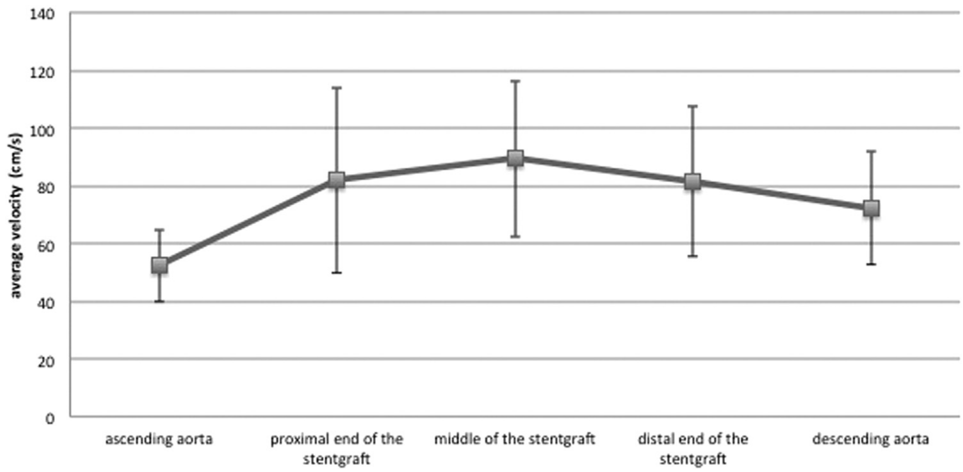

Fig 3. Average velocity of all patients at five different measured points of the aorta. All values are from the outer curvature. The *line* shows the median values and the *bars* show the standard deviation.

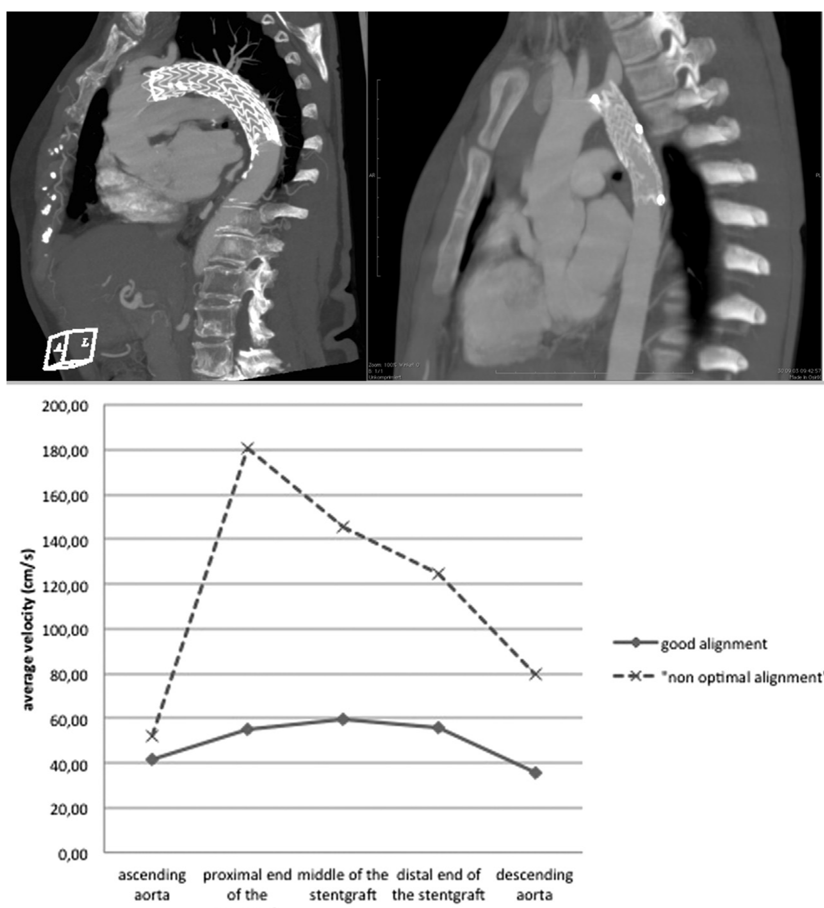

Fig 4. Upper panel, The *left side* shows an example of good alignment at the inner curvature in an elderly woman, and the *right side* shows an example of a young girl with a nonoptimal alignment. **Lower panel,** The average velocities are shown at the five measured points at the outer curvature of two patients. The *dashed line* is the patient with nonoptimal alignment and the *continuous line* is the patient with a good alignment of the stent graft.

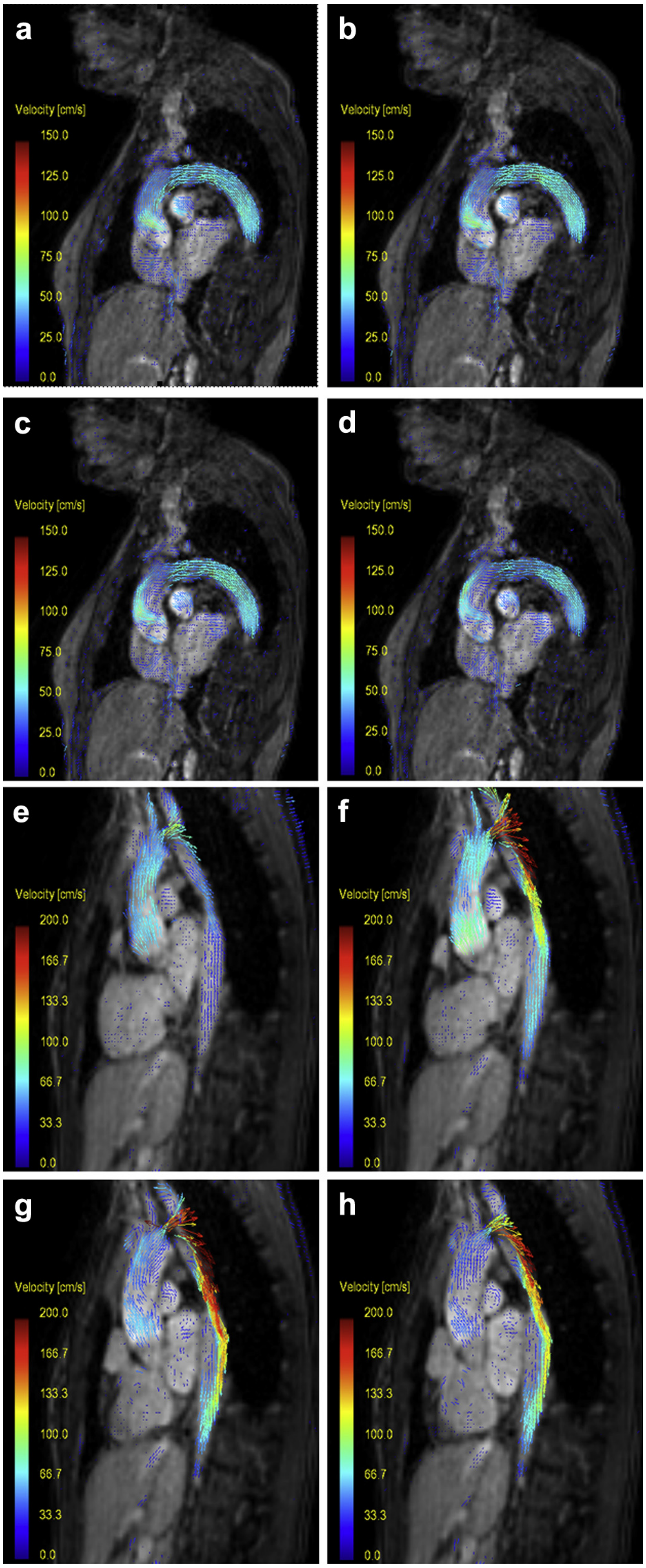

Fig 5. Flow velocity during cardiac cycle. **a-d,** good alignment; **e-h,** nonoptimal alignment: (**a**) 102 ms, (**b**) 136 ms, (**c**) 170 ms, (**d**) 204 ms, (**e**) 64 ms, (**f**) 128 ms, (**g**) 224 ms, (**h**) 288 ms.

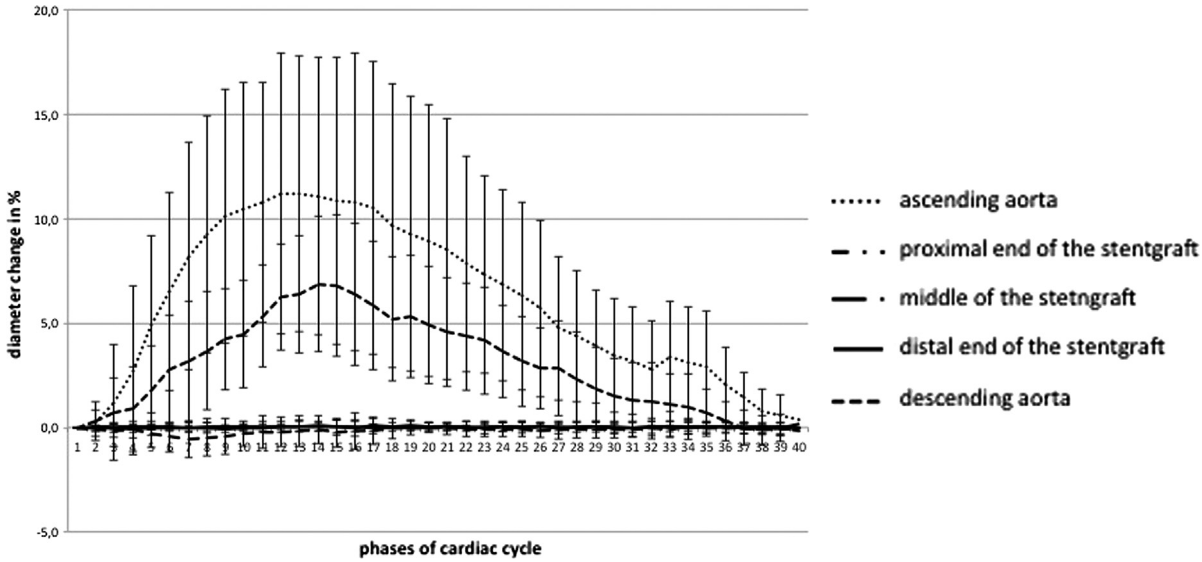

Fig 6. Median changes of the diameter in sagittal slices over the cardiac cycle at different measured points. The *bars* show the standard deviation.

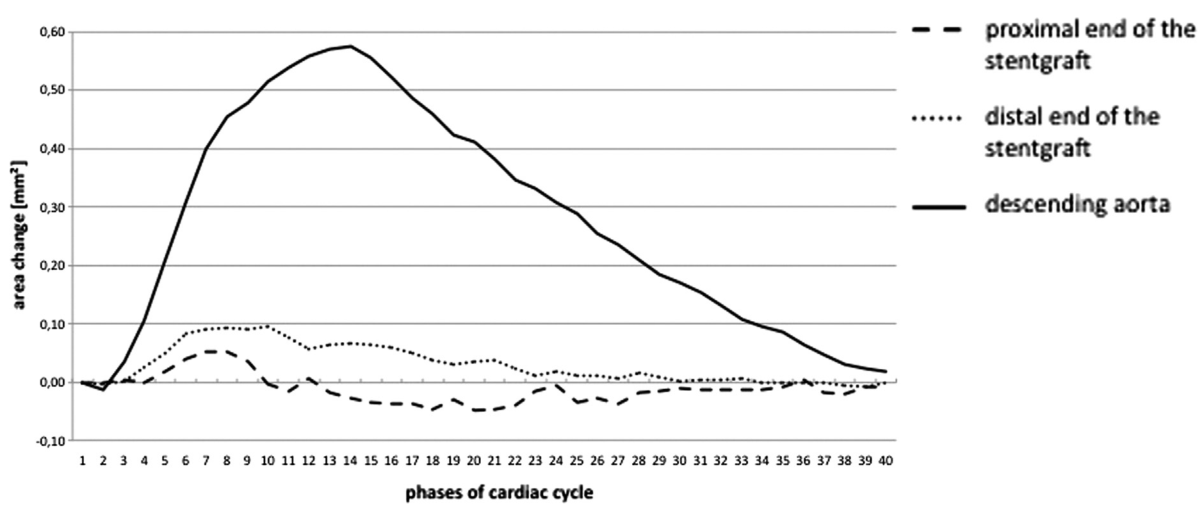

Fig 7. Median change of the area of the aorta at three measured points.

imaging of the blood flow of the entire aortic arch as well as the descending aorta. It allows a deeper insight in the functional position of the stent graft as well as a follow-up in patients with a relevant bird beak. Furthermore, it has the potential to serve as a tool in designing and testing new stent grafts for the aortic arch and fenestrated and branched endografts.

We were able to show that the maximum flow acceleration is at the proximal end of the stent graft and that it correlates with the presence of the bird beak. Nevertheless, no adverse effects were found in the long-term follow-up. The flow pattern remains stable, and no thrombotic apposition or embolic disease was noted.

The untreated aorta showed a physiologic distension over the cardiac cycle. The distension was about 10% in our patients and correlated with results from other groups.[13,14] The Utrecht study analyzed aortic diameter changes in different positions before and after endovascular repair. Van Prehn et al[15] analyzed six patients before and after TEVAR with electrocardiogram-gated CT angiography by measuring diameters and areas in the innominate trunk, aortic arch, and 3 cm in the sealing zone of the stent

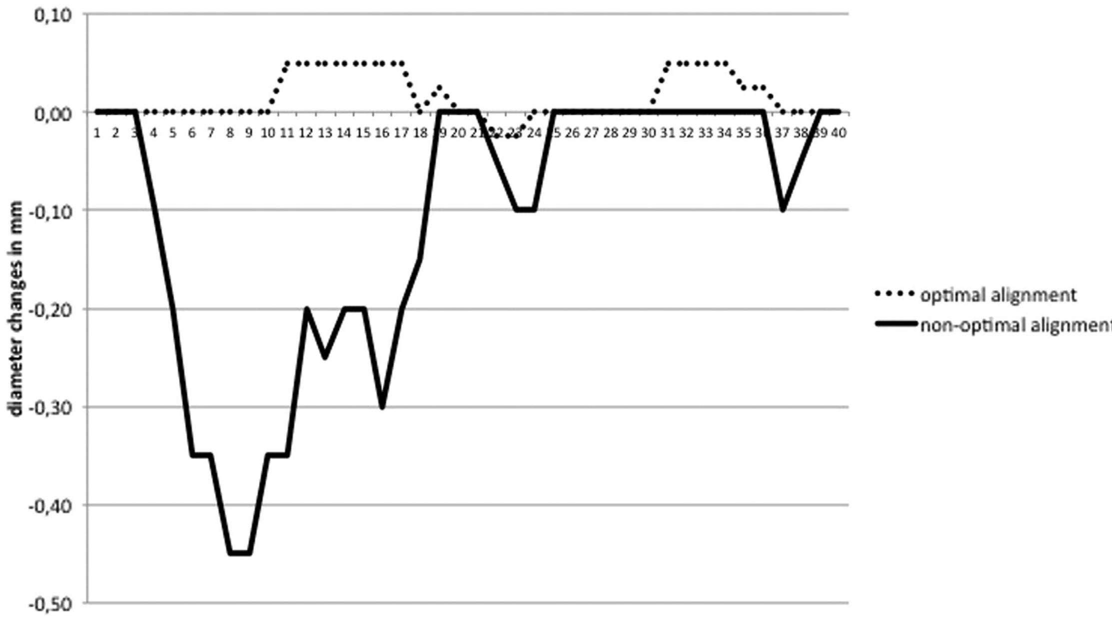

Fig 8. Diameter changes of the stent grafts at the proximal end of a stent graft with an optimal (*dashed line*) and a stent graft with a nonoptimal alignment (*black line*).

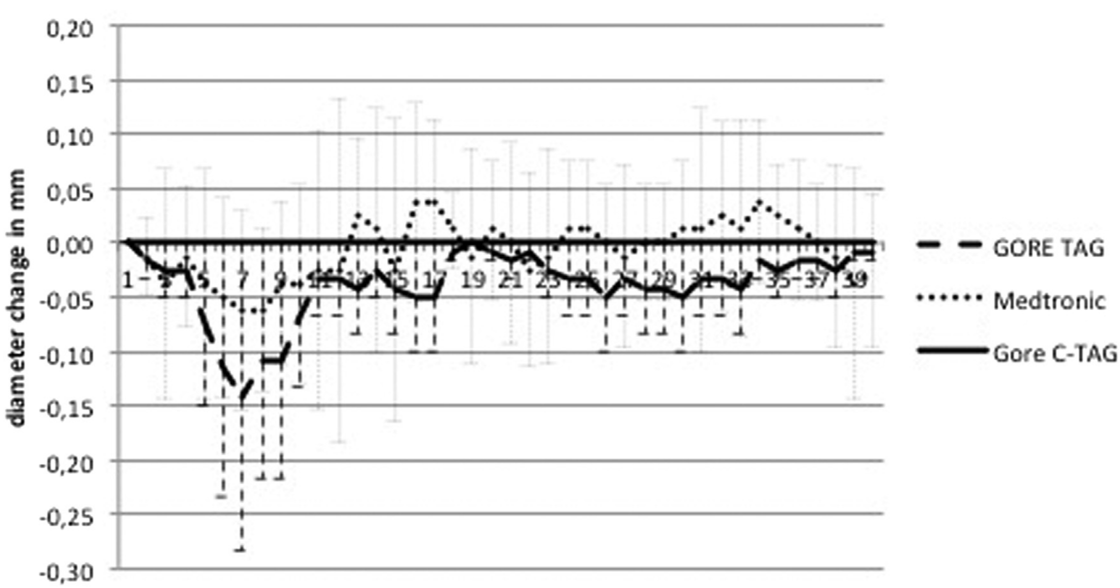

Fig 9. Median changes of the sagittal diameters of the different stent grafts, measured at the proximal end of the stent graft. *C-TAG,* Conformable TAG device (W. L. Gore & Associates, Flagstaff, Ariz); *Gore TAG,* W. L. Gore and Associates; *Medtronic,* Medtronic World Medical, Sunrise, Fla.

graft. The distension of the aorta was similar before and after TEVAR, without significant changes. They found a reduction of diameter and area at the level of the stent graft compared with the preimplant data. We also found a reduction at the proximal level of the stent graft, even if it was only slight. An analysis over the cardiac cycle, such as measurements in the middle of the stent graft and in the descending aorta, is missing.

Van Keulen et al[16] repeated the same study in patients with abdominal stent grafts. The findings were similar. However, the measurements were done at 1 cm in the sealing zone but not in the middle of the stent graft.

CT angiography was used in both studies. The median follow-up was 88 days, whereas follow-up was 3.92 years in our study. Most of our patients had MRI several years after implantation. One patient in our study had MRI 1 day after implantation and we saw no diameter change along the stent graft. All other patients had later MRI, and a comparison over time was not possible.

Ueda et al[17] analyzed their prospective database of TEVAR with the Gore stent graft and found a bird beak configuration in 44%. They found a correlation between extension of bird beak and risk of type Ia and type II endoleaks, mainly by the left subclavian artery. The treated pathologies were transections, aneurysms, dissections, intramural hematomas, and penetrating ulcers. Although all stent grafts showed bird beak configuration, we found no endoleak in our study. The reason might be that we analyzed patients with acute aortic transections only. None of the patients showed atherosclerotic lesions or nonatheromatous plaques. The stent grafts used in those patients were shorter than those used treating other pathologies.

Furthermore, in this study we investigated different stent graft types. The Medtronic and in part the C-TAG have uncovered struts at the proximal end. The hemodynamic relevance is completely different than for the covered parts, because the struts cause turbulences of unknown dimensions.

The longest follow-up was 10.6 years after implantation. A first MRI after 7.8 years in this patient showed no remarkable changes between the two MRIs, despite a moderate bird beak. All changes that we found in flow acceleration and compliance were moderate. This observation was stable over time, except in one patient with a nonoptimal alignment (Fig 4). This patient faced explantation of the stent graft due to a stent graft-induced stenosis with a secondary severe arterial hypertension 9.3 years after implantation. With this exception, no late adverse event or relevant changes were observed over time.

This study has some limitations. The number of patients in the different groups was low, and we know that statistical analysis must be considered very carefully. Another limitation of the actual study was that diameters could be measured only in a sagittal direction. To overcome this problem, orthogonal measurements of the area perpendicular to aorta were also performed. Besides, no absolute values were taken, except for the basic measurement at the beginning of the systole. All other values were recorded as changes in percentage (diameter) or mm^2 (areas) in relation to the basic measurement point. All patients were analyzed after the initial treatment; therefore, we had no baseline MRI before stent graft insertion. A comparison between preoperative and postoperative function would be desirable but was not possible because of the emergency character of the lesion.

CONCLUSIONS

After functional analysis of 26 endovascularly treated patients with acute aortic transections and a follow-up period of 10 years, stent graft long-term functional analysis of more than half showed good results despite the bird beak configuration. This underlines that a minimally invasive treatment of such patients could become more and more the gold standard in the future.

AUTHOR CONTRIBUTIONS

Conception and design: AO, KO, VR
Analysis and interpretation: AO, WR, VR
Data collection: AO, DS, RK, VR
Writing the article: AO, VR
Critical revision of the article: AO, DS, RK, WR, KO, VR
Final approval of the article: AO, DS, RK, WR, KO, VR
Statistical analysis: AO, VR
Obtained funding: AO
Overall responsibility: AO

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